Power Supplies for the Injector Synchrotron Quadrupoles and Sextupoles

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1. Introduction

This light source note will describe the power supplies for the injector synchrotron quadrupole and sextupole magnets.

The injector synchrotron has two families of quadrupole magnets. Each family consists of 40 quadrupole magnets connected in series. These magnets are energized by two phase-controlled, 12-pulse power supplies. Therefore, each power supply will be rated to deliver the necessary power to only 40 quadrupole magnets.

The two families of sextupole magnets in the injector synchrotron each consists of 32 sextupole magnets connected in series, powered by a phase-controlled power supply. Thus, each power supply shall be capable of delivering power to only 32 sextupole magnets.

A typical current waveform for the quadrupole and sextupole magnets consists of a reset section, an injection level section, parabolic section, ramp section, and extraction section. The reset, injection, and extraction levels for quadrupole and sextupole magnets are different.

Two different power supply configurations will be discussed and pros and cons of each configuration will be given. The first configuration proposed for the power supplies, consists of four wye group converters. Two of these wye group converters are connected in parallel via interphase transformers to deliver the necessary current, while two of these parallel combinations are connected in series to provide the required voltage. An L-C-R filter is used to eliminate the high frequency content of the output current. A fast voltage loop along with a high-gain slow-response current loop provides the necessary control to regulate the current in the magnet. A low current level, the current ripple is high, thus a large filter is needed, which adds to the cost of the power supply. However at the high current level the ripple is less severe. The large size of the filter can be reduced by adding an anti-parallel thyristor to the output of the converters. This configuration is shown in Figure 1. When the current is low the thyristor (S1) is turned on before injection and kept on until the current reaches the extraction level. At this time the firing pulse of the anti-parallel thyristor is removed and the wye group converters are

driven harder to back bias the anti-parallel thyristor, allowing it to be turned off so that the power supply can go into inversion mode.

In the second configuration, two full bridge converters are connected in series to deliver the necessary voltage to the load. A split choke is used to eliminate the 720-Hz ripple contents of the output current. An L-C-R filter is used to filter the high frequency harmonics from the output current. One fast response voltage loop along with a high gain, slow response current loop is used to regulate the current in the magnet load. This configuration is given in Figure 2.

The current in the magnet is monitored by means of a high-precision, low-drift, zero-flux current transductor. The transductor senses the magnet current and then provides the controlling signal for the current loop. A 15-bit Digital to Analog Converter (DAC) is programmed by the control computer for the required waveform. The DAC provides the reference signal for the current regulator.

In Section 2, the circuit rating of the quadrupole and sextupole power supplies will be given.
In Section 3 the power supply configuration using the wye group will be discussed and the corresponding parameters for the quadrupole and sextupole power supplies will be calculated.
In Section 4 the power supplies with full bridge configuration will be studied and the required parameters of the quadrupole and sextupole power supplies will be given. Finally in Section 5, a conclusion will be drawn based on the calculations presented in Sections 3 and 4 and some recommendations will be made.
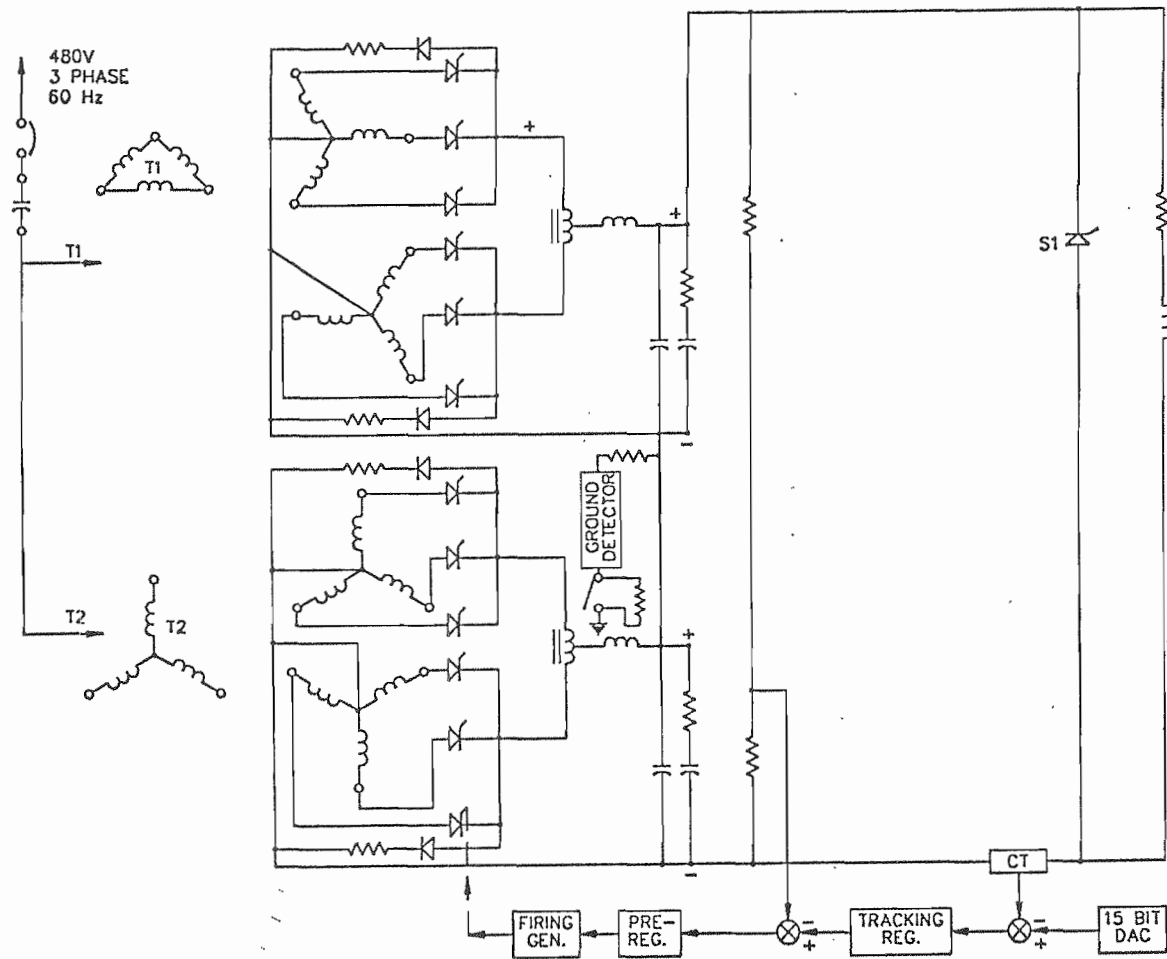
Figure -1 The Block Diagram for Quadrupole and Sextupole Power Supplies Using
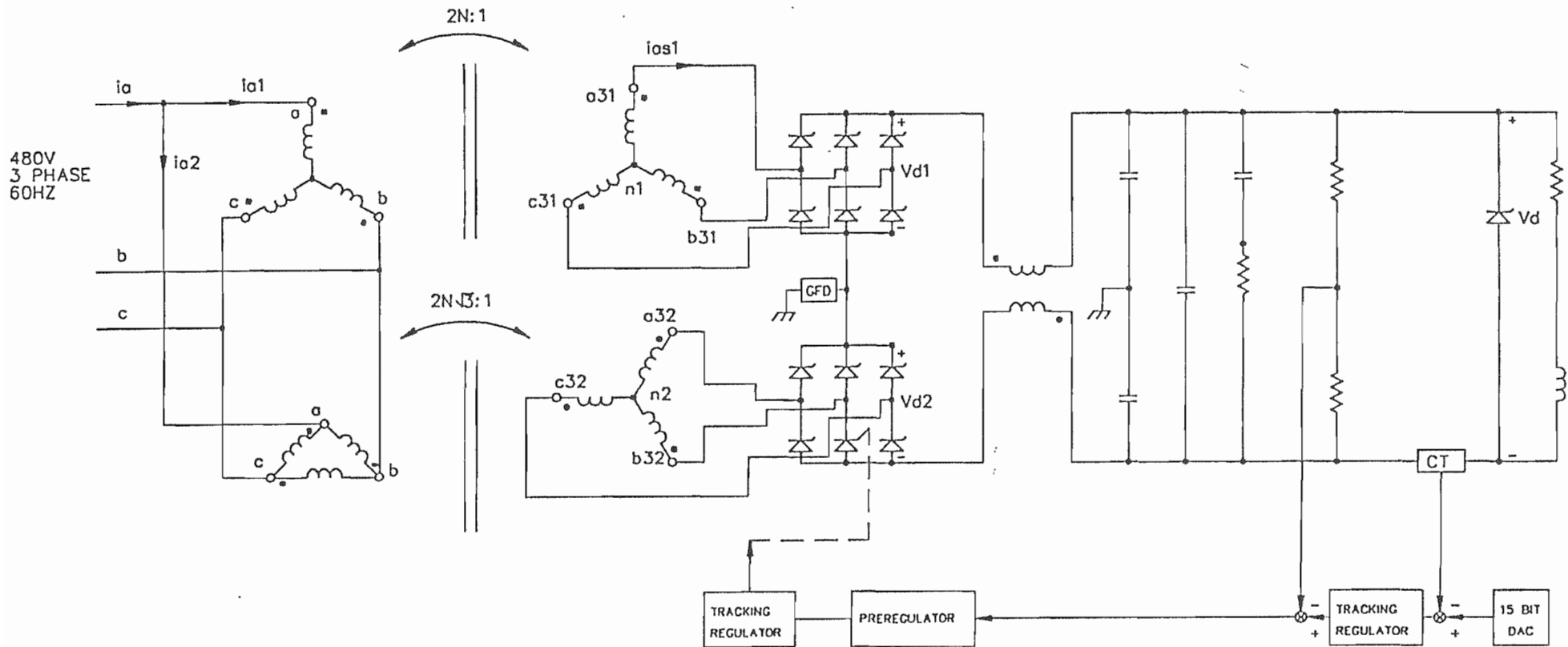Wye Group Configuration

Figure - 2 The Block Diagram for Quadrupole and Sextupole Power Supplies Using
Full Bridge Configuration

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2. Circuit Rating

In the following the circuit rating of Quadrupole and Sextupole power supplies are given [1]:

Table-1

	QUADRUPOLE P.S.	SEXTUPOLE P.S.
Number of power supplies	2	2
Injection Current [A]	38.5	9.1
Extraction Current [A]	659	155
RMS Current [A]	381	90
Number of Magnets	80	64
Resistance of Each Magnet [Ω]	0.0183	0.025
Inductance of Each Magnet [H]	0.00145	0.00038
Injection Voltage [V]	31	8
Extraction Voltage [V]	681	144
Reset Voltage [V]	383	130
RMS Voltage [V]	585	119
P_{max} [kW]	449	23
P_{rated} [kW]	223	11
Total P_{rated} [kW]	446	22
Total kVA	618	31
Input Voltage [V]	480±10%	480±10%
Input Frequency [Hz]	60±0.2	60±0.2
Input Voltage Unbalance	3%	3%
Available Short Circuit Current [kA]	30	30
Maximum Ambient Temperature [°C]	50	50
Minimum Ambient Temperature [°C]	10	10
Cooling Water Temperature [°F]	90±10	90±10
Conductivity [μ–mho/cm]	5	5
Maximum Inlet Pressure [psi]	200	200
Differential Pressure [psi]	70	70
Maximum Pressure that P.S. Withstand [psi]	250	250
Cooling Water Requirement [gpm]	10	1.6
Regulation $\Delta I/I_{max}$		
Reproducibility	$\pm 1 \times 10^{-4}$	$\pm 2 \times 10^{-4}$
Current Ripple	$\pm 2 \times 10^{-4}$	$\pm 3 \times 10^{-4}$
Tracking Error	$\pm 5 \times 10^{-4}$	$\pm 5 \times 10^{-4}$
Resolution of Reference [bits]	15	14

3. Power supplies with wye group configurations

Power supplies with the wye group configuration are shown in Figure 1. Two three-phase transformers are used in the power supply. One transformer has a delta connected primary with two sets of wye connected secondary windings. However, the other transformer has a wye connected primary with two wye connected secondaries. A delta connected tertiary winding is also provided to eliminate the zero sequence current. Two interphase transformers are used to connect the outputs of the converters in parallel. Figure 1 clearly shows the connection of these interphase transformers. The phasor diagram for voltages at the secondary windings of the transformers is given in Figure 3.
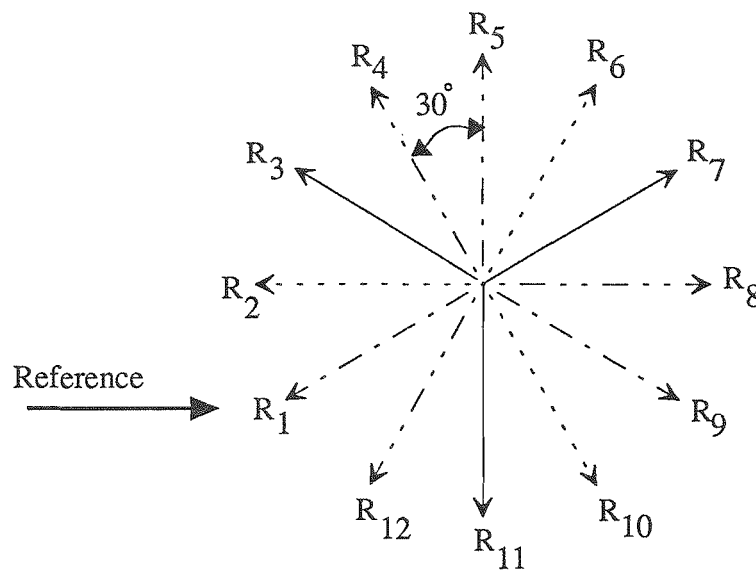

Figure-3   Voltage Phasor Diagram at Secondary Windings of Transformers

3.1 Transformer and Thyristors Rating

In order to provide the current and voltage required to operate the magnets, the following parameters for each transformer and thyristor are specified:

Table-2

	QUADRUPOLE P.S.	SEXTUPOLE P.S.
Transformer Rating:		
Input Voltage [Vac @ 60 Hz]	480	480
Secondary Line to Line Voltage [V]	433	88
Secondary rms Line Current [A]	111	27
Apparent Power[kVA @ eff. 85%*]	309	14.9
Input Current [A]	372	18
Impedance [on per unit base]	5%	5%
No. of Transformers Windings	6	6
Transformer Temperature Rise [°C]	30	30
Cooling Water Required [gpm]	4	0.3
Line Voltage Imbalance [%]	±3	±3
Thyristor Rating		
Average Current Rating [A]	190	45
Peak On-State Voltage [V]	2.5	2.5
Peak Reverse Blocking Voltage [V]	1425	300
Power Dissipation Due to Thyristors [kW]	2.85	0.675
Voltage Drop Due to the Thyristors [V]	5	5

* The efficiency of the transformer must be higher than 85%, however this value is used to calculate the cooling water requirement.

3.2 Interphase Transformers

In order to connect two half-wave converters in parallel, an interphase transformer is used. The use of the interphase transformer allows two of the half-wave converters that are connected in parallel to operate for the maximum of a 120° conduction angle and share the load current. The interphase transformer basically consists of a core and a coil with a center tap. When the two half-wave converters are contributing equal amounts of voltage the interphase transformer is transparent. However, when the output voltage of the half-wave converters are not equal the windings of the interphase transformer show enough impedance to support the voltage imbalance. Each leg of the interphase transformer is assumed to have 1 mH inductance and 10 mΩ resistance. This amount of inductance is sufficient to support 20% voltage mismatch across the interphase transformer. The current produced due to the 20% voltage mismatch should not saturate the core of the interphase transformer.

3.3 Filter Design

The basic ripple frequency of the power supply is 720 Hz. However, due to imbalance in the transformers, ripples with frequencies lower than 720 Hz can appear in the power supply output. A filter with very low cut-off frequency can eliminate all ripple frequencies. However, such a filter will produce a high cost power supply with a relatively slow time response. Therefore, filters with cut-off frequencies of 51 Hz for quadrupole and 40 Hz for sextupole power supplies are designed to eliminate all ripple frequencies above 60 Hz. The filters for the sextupole power supplies are larger and have lower cut-off frequency because the sextupole magnets have less filtering effect than the quadrupole magnets due to their low inductance. The circuit diagram for such a filter is given in Figure 4. The filter consists of an inductance, two capacitor banks, and a damping resistor. The transfer function of such a filter is given in the following [2].

$$\frac{e_o}{e_i} = \frac{(sT_2 + 1)}{s^3 T_2 L_1 C_1 + S^2 (T_1 T_2 + L_1 C_2) + s(T_1 + T_2 + T_3) + 1} \tag{1}$$

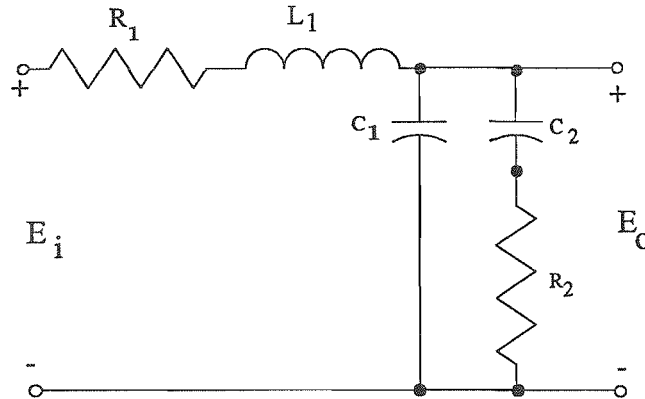where $T_1 = R_1 C_1$, $T_2 = R_2 C_2$ and $T_3 = R_1 C_2$

Figure-4 Low Pass Filter for Quadrupole and Sextupole Power Supplies

The design parameters for filters used in the quadrupole and sextupole power supplies are given below:

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Table-3

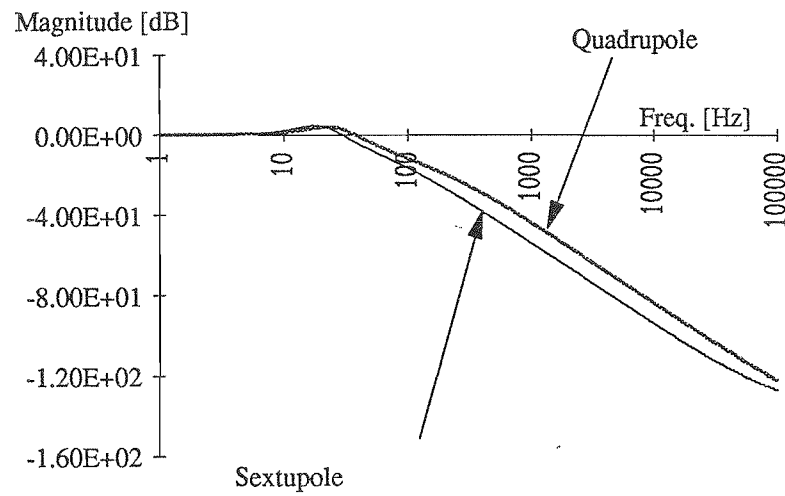|	QUADRUPOLE P.S.	SEXTUPOLE P.S.
Inductance - L_1 [mH]	1.0	1.0
Resistance of Inductance - R_1 [mΩ]	1.0	1.0
Capacitance - C_1 [μF]	958	15832
Capacitance - C_2 [μF]	9580	3167
Damping Resistance - R_2 [Ω]	0.65	0.51
Cut off Frequency [Hz]	51	40

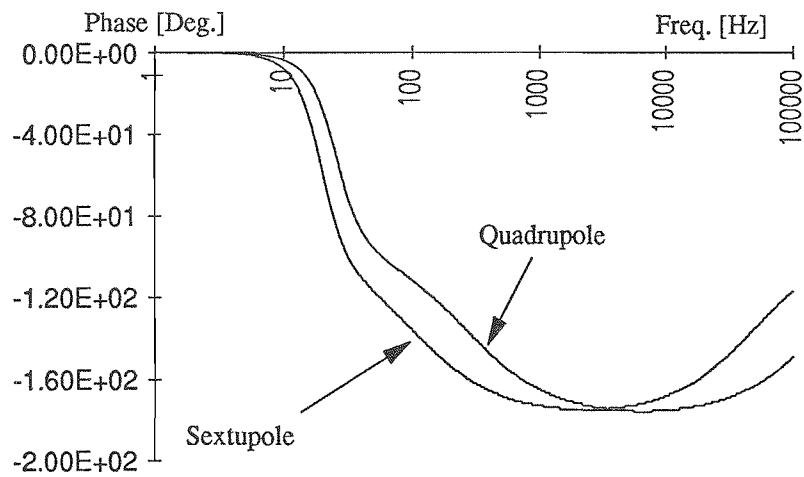Figure -5   Magnitude Response for Quadrupole and Sextupole Power Supply Filters

Figure -6   Phase Response for Quadrupole and Sextupole Power Supply Filers

3.4 Control Scheme for Quadrupole and Sextupole Power Supplies

Two control loops are utilized to regulate the current in the magnet chain. These loops consist of a slow-response, high-gain current loop and a fast-response voltage loop. A high-precision, low-drift, zero-flux current transductor is used to sense the current in the magnet chain. A true 15-bit DAC for quadrupole power supplies and a true 14-bit DAC for sextupole power supplies, which are programmed by the control computer for the required current level, provide the references for the current regulators in quadrupole and sextuple power supplies. The difference between the current reference and the current transductor output is fed to a high-precision, proportional plus integral (PI) controller. This controller provides the controlling signal for the thyristor firing circuit, and subsequently the firing circuit provides triggering pulses to the thyristors in the converters.

3.5 Controller

In order to regulate the magnet current, a proportional control is usually needed. However, this control scheme always requires a small input signal in order to operate, which results in an offset between the magnet current and the reference. This problem can be somewhat alleviated by increasing the proportional gain of the controller, but high proportional gain may result in an oscillation, which is undesirable. A better approach to the problem of providing a controller with a zero offset is to introduce an integrator to the controller, which will eliminate the offset current. For the fast-response voltage loop and high-gain current loops, proportional plus integral controllers are used. The block diagram for the suggested control circuit along with the firing circuit is given in Figure 7. The voltage and current loop time responses must be set correctly in order to obtain a proper control of the current in the magnet load. Thus, the voltage loop controller response time is set to correct for 720 Hz ripple, while the current loop controller response time is set equal to the response time of the load magnet.

3.6 Firing Circuit

The firing signal generator consists of a blanking logic, ramp generator, comparator, amplifier and pulse transformers. A precision ramp generator generates a chain of linear and equal ramp waveforms. The blanking logic circuit generates a sequence of 12 pulses per line cycle. These pulses are used to produce a sequence of twelve ramp signals via ramp generator circuits. Only one of the pulses in the blanking logic circuit is synchronized with the line, the remaining eleven pulses are generated through an electronic time delay circuit. A comparator is used to compare the ramp signal with the reference signal given by the current and voltage controllers, which produces firing pulses for the thyristors. These pulses are amplified to obtain sufficient current to drive the 12 thyristors in the converters. The trigger pulses are fed to the gates of the thyristors via pulse transformers.
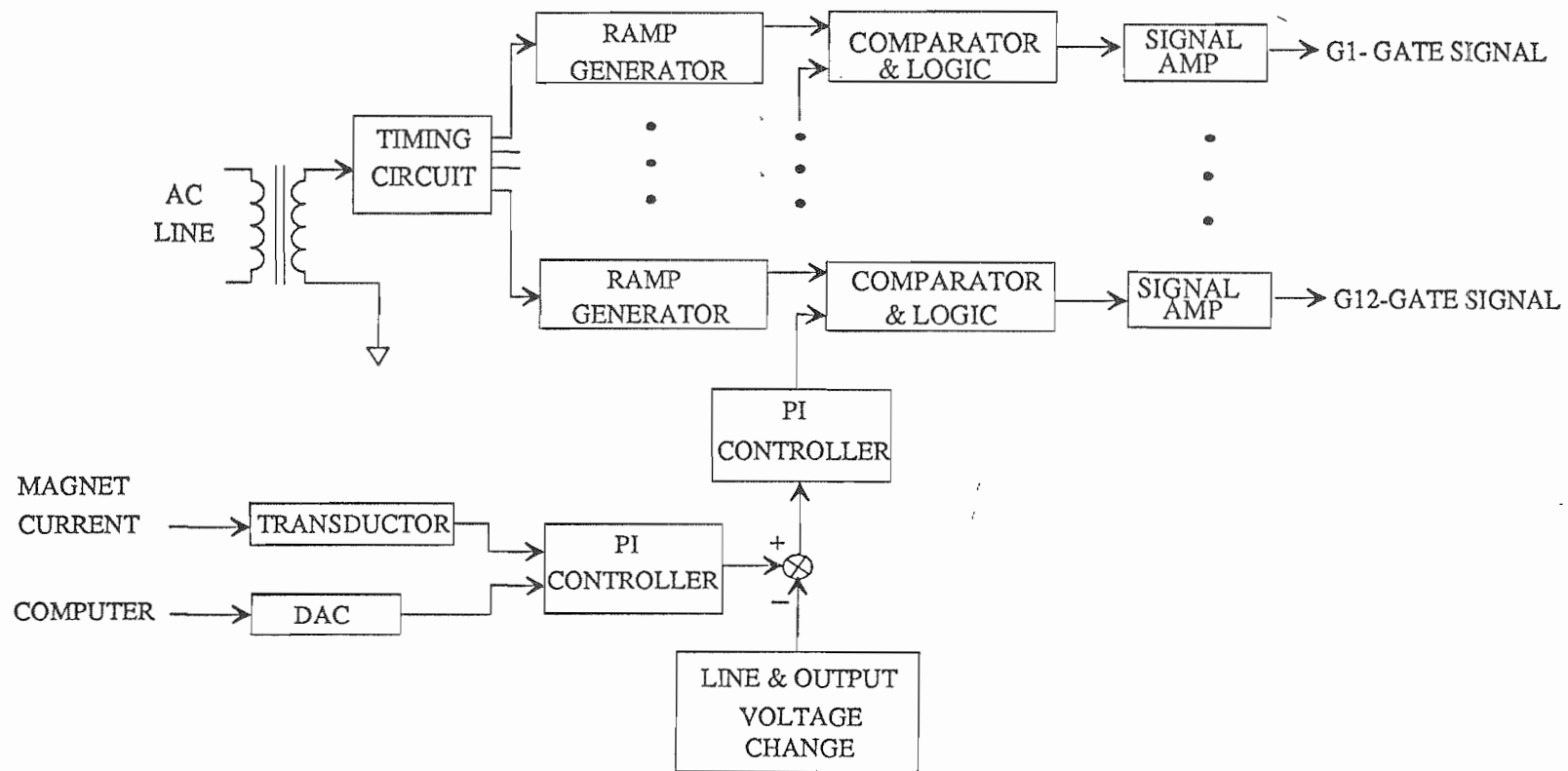
Figure 7. Triggering Circuit Block Diagram

3.7 Calculation of Power Supply Rating

The power rating of the quadrupole and sextupole power supplies are calculated as shown below.

Quadrupole Power Supplies:

Voltage Rating: For half of the magnet chain (40 magnets) the voltage drop will be calculated as follows:

$$V = RI + L\frac{\Delta I}{\Delta t} \tag{4}$$

where $R = 40 \times 0.0183\ \Omega$, $L = 40 \times 0.0015\ H$, $\Delta I = 659\ A$ and $\Delta t = 250\ ms$, thus: $V = 681\ V$.
The rms value for the current and voltage is calculated as follows:

$I_{rms} = \dfrac{I_{peak}}{\sqrt{3}}$ where $I_{peak} = 659\ A$ and then $I_{rms} = 381\ A$.

Using the trapezoidal waveform of the voltage across the magnet for one cycle, the rms value of voltage is calculated as:
$V_{rms} = 585\ V$

Injection Voltage: The voltage drop due to the magnets' resistance is calculated as follows:
$V_{in} = 38 \times 40 \times 0.0183 \times 1.1 = 31\ V$ and the voltage contribution due to Ldi/dt will be as:
$V_{in} = 31 + 40 \times .0015 \times (659 - 38.5)/.250 = 180\ V$

Extraction Voltages:
$V_{ext-min} = 40 \times 0.0183 \times 659 \times 1.1 = 531\ V$ and
$V_{ext-max} = 531 + 40 \times .0015 \times (659 - 38.5)/.250 = 681\ V$

Maximum Power:
$P_{max} = 681 \times 659 = 448.8\ kW$

Rated Power:
$P_{rated} = 585 \times 381 = 222.3\ kW$

Reset Voltage:
$V_{reset-max} = 681 - (180-31) - (180-31) = 383\ V$
$V_{reset-min} = 31 + 382 - 531 = -118\ V$

Sextupole Power Supplies:

Voltage Rating: For half of the magnet chain (32 magnets) the voltage drop will be calculated from equation (4), where $R = 32 \times 0.025\ \Omega$, $L = 32 \times 0.0004\ H$, $\Delta I = 155\ A$ and $\Delta t = 250\ ms$,

thus assuming 10% for cable drop then V = 143.6 V. The rms values for the current and voltage are calculated as follows:

$$I_{rms} = \frac{I_{peak}}{\sqrt{3}} \quad \text{where } I_{peak} = 155 \text{ A then } I_{rms} = 89.5 \text{ A.}$$

Using the trapezoidal curve of the voltage across the magnet for one cycle, the rms value of voltage is:

$V_{rms} = 119$

Injection Voltage:

$V_{in} = 32 \times 0.025 \times 9.1 \times 1.1 = 8.0$ V, and the voltage contribution due to Ldi/dt for the injection voltage will be:

$V_{in} = 8.00 + 32 \times 0.00038 \times (155-9.1)/.250 = 15.1$ V

Extraction Voltage:

$V_{ext-min} = 32 \times 0.025 \times 155 \times 1.1 = 136.4$ V and

$V_{ext-max} = 136.4 + 32 \times .00038 \times (155-9.1)/.250 = 143.6$ V

Maximum Power:

$P_{max} = 143.6 \times 155 = 22.2$ kW

Rated Power:

$P_{rated} = 118.2 \times 89.5 = 10.6$ kW

Reset Voltage:

$V_{reset-max} = 143.6 - 7.1 - 7.1 = 129.4$ V

$V_{reset-min} = 8 + 129.4 - 136.4 = 1$

The current and voltage waveforms for quadrupole and sextupole power supplies are given in Figures 8 and 9, respectively.

The average output voltage of each three-phase half-converter is given by [3] as follows

$$V_{dc} = 3V_m \frac{\sqrt{3}}{2\pi} \text{Cos}\alpha \qquad (5)$$

The rms value of the output voltage for each three-phase half-wave converter is given by the following equation:

$$V_{rms} = \sqrt{3} V_m (\frac{1}{6} + \frac{\sqrt{3}}{2\pi} \text{Cos}2\alpha)^{1/2} \qquad (6)$$
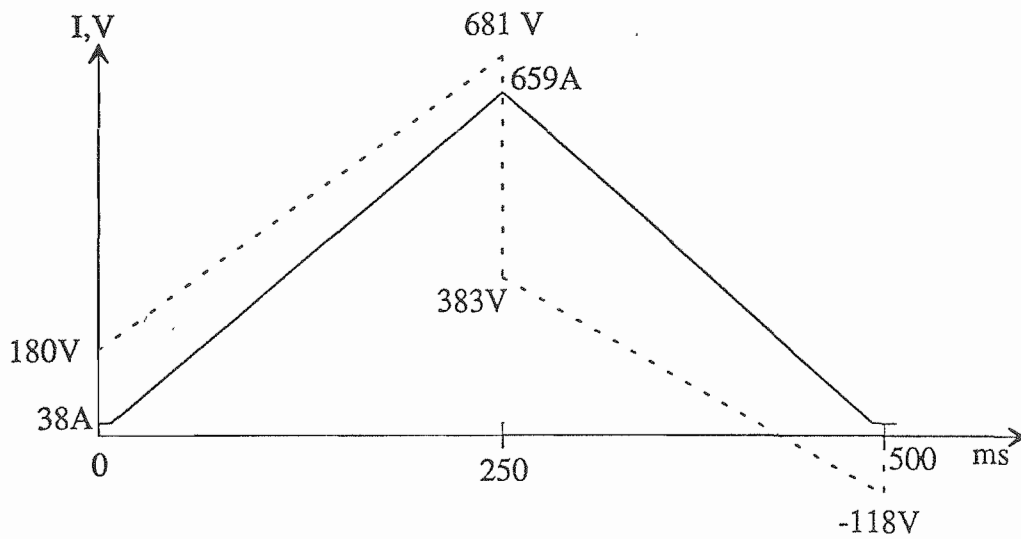
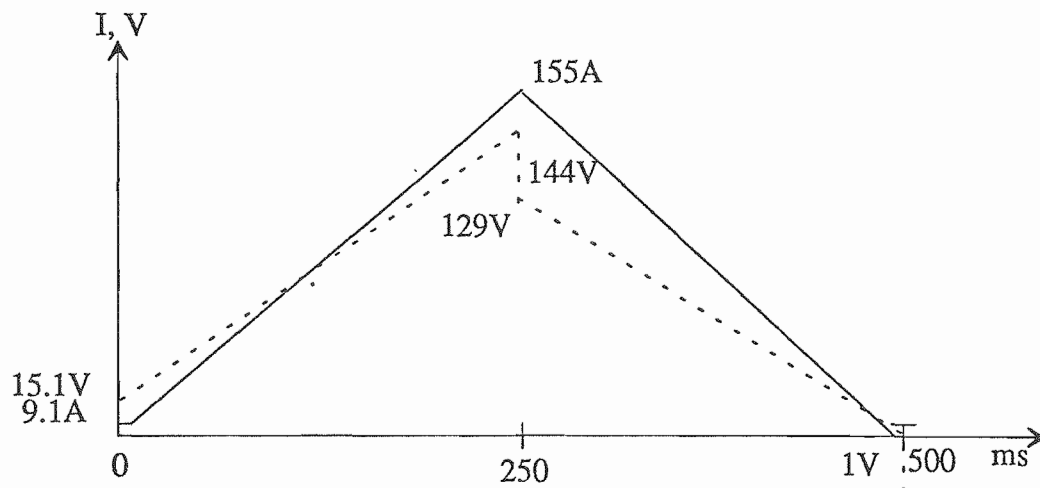Figure-8 Output Current and Voltage Waveforms for Quadrupole
Power Supplies

Figure-9 Output Current and Voltage Waveforms for Sextupole
Power Supplies

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and the output voltage harmonic for the three-phase half-wave converters is calculated via the following equation :

$$V_h = 3\,V_m\,\frac{\sqrt{3}}{2\pi}\sum_{p=1}^{\infty}(-1)^p\left\{\frac{\cos(3p\omega_0 t+(3p+1)\alpha)}{(3p+1)} - \frac{\cos(3p\omega_0 t+(3p-1)\alpha)}{(3p-1)}\right\} \tag{7}$$

where V_m is the peak voltage value of the ac source , α is the firing angle of the converter, p is the harmonic order and ω_0 is the fundamental frequency of the converter.

The input power factor is defined as:

$$PF = \frac{V_{rms}I_1}{V_{rms}I_{rms}}\cos(\phi) \tag{8}$$

where I_1 is the fundamental rms component of the input current, and ϕ is the displacement angle between the fundamental components of the input current and voltage. It must be noted that because the power supply output voltage and current are not fixed, the power factor of the power supply will not be a constant number.

In a three-phase half-wave converter,   the average dc output voltage will be reduced due to the voltage drop in the converter transformer.   Thus the output dc voltage of the converter is calculated as:

$$V_d = 3V_m\,\frac{\sqrt{3}}{2\pi}\cos\alpha - \frac{3\omega L_s}{2\pi}I_d \tag{9}$$

where L_s is the per-phase inductance of the transformer and I_d is the dc output current of the power supply.

3.8 Power Supply Cooling Water Requirement

One gallon of water per minute can cool 1 kW power dissipation with a 6.8 °F temperature rise. For solid state devices we design for a 14 °F (7.8 °C) temperature rise. For quadrupole power supplies a 190 A current passes through each SCR at 2.5 V voltage drop,   then the total power

loss for 28 SCRs will be 13.3 kW. This power loss requires 13.3 x 6.8/14 = 6.46 gal/min cooling water to provide only 14 °F of temperature rise.

For buses and transformers a temperature rise of 30 °C (54 °F) is assumed. We assume that no more than 15% of the total power (66.6 kW) is lost through buses and transformers, with 80% of these losses cooled via water and the other 20% of power losses cooled through convection cooling. Therefore, for a 54 °F temperature rise, the amount of cooling water needed is calculated to be: 66.6 x 0.8 x 6.8/54 = 6.7 gal/min. Thus, the total amount of cooling water needed for two quadrupole power supplies is 6.7 + 6.46 = 13.2 gal/min. For the rating of power supplies 14 gal/min cooling water is specified.

If we use the same method to calculate the cooling water requirement of the sextupole power supplies, the required cooling water will be 3.74 gpm.

4. Power Supplies with Full Bridge Configuration

A 12-pulse converter using two 6-pulse full bridge converters, a wye-wye and a delta-wye connected transformer is shown in Figure 2. The per-phase currents i_{a1} and i_{a2} are given by the following equations [4]:

$$i_{a1} = \frac{2\sqrt{3}}{2N\pi} I_d \left(\cos\theta - 1/5 \cos5\theta + 1/7 \cos7\theta - 1/11 \cos11\theta + 1/13 \cos13\theta \ldots \right) \qquad (10)$$

and

$$i_{a2} = \frac{2\sqrt{3}}{2N\pi} I_d \left(\cos\theta + 1/5 \cos5\theta - 1/7 \cos7\theta - 1/11 \cos11\theta + 1/13 \cos13\theta \ldots \right) \qquad (11)$$

where θ is ωt and the transformer ratio N is indicated in Figure 2. Therefore the combined current drawn from the line by the 12-pulse converter is given by:

$$i_a = i_{a2} + i_{a1} = \frac{2\sqrt{3}}{2N\pi} I_d \left(\cos\theta - 1/11 \cos11\theta + 1/13 \cos13\theta \ldots \right) \qquad (12)$$

This Fourier analysis shows that the combined line current has harmonics of order

$$h = 12 k \pm 1 \quad (\text{where } k \text{ is an integer}) \qquad (13)$$

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resulting in a 12-pulse operation. The harmonic current amplitudes in equation (12) for a 12-pulse converter are inversely proportional to their harmonic order and the lowest order harmonics are the eleventh and the thirteenth. The currents on the ac side of the two 6-pulse converters add up, confirming that the two converters are effectively in parallel on the ac side.

On the dc side, the voltage waveforms V_{d1} and V_{d2} are shifted by 30 degrees with respect to each other. Since the two 6-pulse converters are connected in series on the dc side, the total dc voltage $V_d = V_{d1} + V_{d2}$ has 12 ripple pulses per fundamental frequency of the ac side. This results in the voltage harmonics of the order h in V_d, where:

$$h = 12 \, k \quad \text{(k is an integer)} \tag{14}$$

and the twelfth harmonic is the lowest order harmonic. The presence of the transformer inductance L_s does not change the order of the characteristic harmonics produced either on the ac side or the dc side, provided that the two 6-pulse converters operate under identical conditions. However, the harmonic magnitudes depend significantly on L_s, the delay angle α, and the dc current I_d. The effect of L_s on the dc voltage output is given by the following equation:

$$V_{d1} = V_{d2} = \frac{V_d}{2} = \frac{3\sqrt{2}}{\pi} V_{LL} \, \text{Cos} \, \alpha - \frac{3 \, \omega \, L_s}{\pi} I_d \tag{15}$$

where V_{LL} is the line-to-line rms voltage applied to each of the 6-pulse converters, and L_s is the per-phase leakage inductance of each of the transformers referred to the converter side.

There are two modes of operations for the full bridge converters. These are the rectifier and inverter modes of operations. In the following section these two modes of operations will be briefly discussed.

4.1 Rectifier Mode of Operation

The value of the delay firing angle, α, determines a specific mode of operation of the converters. For $0° \leq \alpha \leq 90°$ the converters operate in the rectifier mode and the converter will have 120° conduction. The real power, P, and reactive power, Q, of the converters in this mode of operation are given in the following equations:

$$P = 2.7 \, V_{LL} \, I_d \, \text{Cos}\alpha - \frac{6\omega L_s}{\pi} I_d \tag{16}$$

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$$Q = 2.7 \, V_{LL} \, I_d \, \text{Sin}\alpha \; - \; \frac{6\omega L_s}{\pi} I_d \tag{17}$$

It will be noticed that the power transformer's impedance L_s can reduce the amount of the power to be transferred. The reactive power Q is directly proportional to the dc current I_d, thus an increase in the dc current demands more reactive power from the electrical system, which must be provided. In order to deliver such a reactive power an ac capacitor bank is usually installed on the ac side of the converters. This capacitor bank not only provides the necessary reactive power for the converter, it also eliminates the higher harmonic components which are introduced to the ac system by the converter.

4.2 Inverter Mode of Operation

In the inverter mode, power transfer is from the dc side to the ac side of the converter. The firing angle must be $90° \leq \alpha \leq 180°$. The real and reactive powers are given by the equations (16) and (17), respectively.

4.3 Components Rating

The transformer and thyristor ratings are shown in Table 4.

Table-4

	QUADRUPOLE P.S.	SEXTUPOLE P.S.
Transformer Rating:		
Input Voltage [Vac @ 60 Hz]	480	480
Secondary Line to Line Voltage[V]	217	88
Secondary rms Line Current [A]	220	52
Apparent Power [kVA @ eff. 85%*]	309	14.9
Input Current [A]	372	18
Impedance [on per unit base]	5%	5%
No. of Transformers Windings	4	4
Transformer Temperature Rise[$^\circ$C]	30	30
Cooling Water Required [gpm]	3.3	1.1
Line Voltage Imbalance [%]	±3	±3
Thyristor Rating:		
Average Current Rating [A]	380	90
Peak On-State Voltage [V]	2.5	2.5
Peak Reverse Blocking Voltage [V]	715	152
Power Dissipation Due to Thyristors [kW]	5.7	1.35
Voltage Drop Due to Thyristors [V]	10	10

*   The efficiency of the transformer must be higher than 85%,   however this value is used to calculate the cooling water requirement.

4.4 Comparison of two proposed configurations

Power supply configurations using wye group converters and full bridge converters were analyzed in sections 3 and 4 respectively. The number of 3-phase windings used in the configuration given in Table 2 is 6, while this number for the configuration given in Table 4 is only 4. This reduction in the number of windings contributes to the reduction of the power transformer size when the full bridge configuration is utilized.

The average current rating of the thyristors used in the configuration presented in Table 2 is 190 A and the peak reverse blocking voltage is 1425 V, while the corresponding values for the configuration presented in Table 4 are 380 A and 715 V, respectively. Thus, the power

configuration using full bridge converters requires thyristors with twice the current and half the reverse voltage blocking capability of the configurations with wye group converters. For high-voltage applications where the reverse blocking voltage of the thyristors must be above 5000 V several thyristors need to be connected in series to provide the necessary blocking capability because thyristors available at the present time have a maximum reverse blocking voltage of only 5000 V. However, thyristors in the full bridge configuration require only half the reverse blocking voltage compared with those in the wye group configuration. Thus, for high-voltage applications the full bridge configuration for the converters is preferable. On the other hand, the thyristors in the full bridge configuration must carry twice the current compared with those in the wye group configuration. Moreover, the voltage drop due to the thyristors in the full wave configuration is twice the corresponding voltage drop in the wye group configuration. Therefore, for high-current, low-voltage applications the configurations which utilize the wye group converters are advantageous.

5. Interlocks
In order to operate the power supplies safely and protect them against faults and overloading, the following interlocks are needed.

1) Faults: Any fault such as line to line, line to ground , and short circuit of the output power will be detected and consequently the power supply will be turned off.

If any of the following take place the power supply will trip off.
2) Low water flow
3) Over temperature water
4) Transformer and choke over temperature
5) SCRs over temperature
6) AC line current imbalance and AC over current (an indication of excessive AC input current)
7) DC over current to ground (an indication of excessive flow of DC current to ground)
8) DC over current indicator
9) Door open.

The following parameters will be monitored continuously:

1) AC line voltage
2) AC line current
3) DC output voltage
4) DC output current

5) Power supply cabinet temperature.

The following signals will be the inputs to the power supply:

1) Reset Interlocks
2) Power ON
3) Power OFF
4) Count up/ count down signals.

6. Conclusion

Two different configurations for the synchrotron quadrupole and sextupole power supplies were discussed and the corresponding parameters of these power supplies for both configurations were derived. Certain parts of the power supplies such as the control section, firing circuits, and interlocks can be similar for both configurations, thus these parts were only presented in section 3 of this note. It was concluded that the power supplies using wye group converters are preferable for high-current, low-voltage applications whereas power supplies using full bridge converters are more desirable for high-voltage, low-current applications. Both of the configurations utilize 12-pulse in rectifier and inverter modes. Power supplies using wye group converters are more efficient than those employing full bridge converters. However, the power transformer design and fabrication for the power supplies with full bridge arrangements are somewhat simpler than those utilizing wye group converters. Moreover, the requirement for interphase transformers in the power supplies with wye group converters adds to the complexity of the design and fabrication.

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